

Probing the coupling of heavy dark matter to nucleons by detecting neutrino signature from the Earth core

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We argue that the detection of neutrino signature from the Earth core is an ideal approach for probing the coupling of heavy dark matter ($m_\chi > 10^4$ GeV) to nucleons. We first note that direct searches for dark matter (DM) in such a mass range do not provide stringent constraints. Furthermore the energies of neutrinos arising from DM annihilations inside the Sun cannot exceed a few TeV at the Sun surface due to the attenuation effect. Therefore the sensitivity to the heavy DM coupling is lost. Finally, the detection of neutrino signature from galactic halo can only probe DM annihilation cross sections. After presenting the rationale of our studies, we discuss the event rates in IceCube and KM3NeT arising from the neutrino flux produced by annihilations of Earth-captured DM heavier than 10^4 GeV. The IceCube and KM3NeT sensitivities to spin independent DM-proton scattering cross section $\sigma_{\chi p}$ and isospin violation effect in this mass range are presented. The implications of our results are also discussed.

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1 Introduction

Evidences for the dark matter (DM) are provided by many astrophysical observations, although the nature of DM is yet to be uncovered. DM can be detected either directly or indirectly where the former observes the nucleus recoil as DM interacts with the target nuclei in the detector while the latter detects final state particles resulting from DM annihilations or decays. The current direct DM search limit on $\sigma_{\chi p}$ is up to 10 TeV mass only. Beyond 10 TeV mass, the indirect searches such as IceCube and KM3NeT may use Earth as a target to probe $\sigma_{\chi p}$.

The flux of DM induced neutrinos from galactic halo is only sensitive to $\langle\sigma v\rangle$. Furthermore, the energies of neutrinos from the Sun can not exceed a few TeVs due to severe energy attenuations through the propagations. With the above reasons, Earth is an ideal place to probe heavy DM couplings to nucleons.

In this work, we study both muon track events and cascade events induced by neutrinos. We consider annihilation channels $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ for signature neutrino productions. Recent studies [1, 2] also suggested that DM-nucleon interactions do not necessarily respect isospin symmetry. Therefore isospin violation effect is also taken into consideration in our analysis.

2 Neutrino signals from DM and atmospheric background

2.1 DM capture and annihilation rates in the Earth core

The neutrino differential flux Φ_{ν_i} from $\chi\chi \rightarrow f\bar{f}$ can be expressed as

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = P_{\nu_j \rightarrow i}(R_{\oplus}, E_{\nu}) \frac{\Gamma_A}{4\pi R_{\oplus}^2} \sum_f B_f \left(\frac{dN_{\nu_j}}{dE_{\nu_j}} \right)_f \quad (1)$$

where R_{\oplus} is the Earth radius, $P_{\nu_j \rightarrow i}$ is the neutrino oscillation probability from flavor j to i after propagating from the source to the detector, B_f is the branching ratio corresponding to the channel $\chi\chi \rightarrow f\bar{f}$, dN_{ν}/dE_{ν} is the neutrino spectrum, and Γ_A is the DM annihilation rate in the Earth.

The annihilation rate, Γ_A , can be obtained by solving the DM evolution equation in the Earth core [3, 4]

$$\dot{N} = \Gamma_C N - C_A N^2 - C_E N \quad (2)$$

where N is the DM number density in the Earth core, Γ_C is the capture rate, and C_E is the evaporation rate. The evaporation rate is only relevant when $m_{\chi} \lesssim 5$ GeV [5] and can be ignored in this work. Solving Eq. (2) thus gives

$$\Gamma_A = \frac{C_A}{2} N(t)^2 = \frac{\Gamma_C}{2} \tanh^2 \left(\frac{t}{\tau_{\oplus}} \right) \quad (3)$$

where t is the lifetime of the solar system and τ_{\oplus} is the time scale when the DM capture and annihilation in the Earth core reaches the equilibrium state. The capture rate, Γ_C , is proportional to

$$\Gamma_C \propto \left(\frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{270 \text{ km s}^{-1}}{\bar{v}} \right) \left(\frac{\text{GeV}}{m_\chi} \right) \left(\frac{\sigma_{\chi p}}{\text{pb}} \right) \sum_{\mathcal{A}} F_{\mathcal{A}}^*(m_\chi) \quad (4)$$

where ρ_0 is the local DM density, \bar{v} is the DM velocity dispersion, $\sigma_{\chi p}$ is the DM-nucleon cross sections, and $F_{\mathcal{A}}^*(m_\chi)$ is the product of various factors for element \mathcal{A} including the mass fraction, chemical element distribution, kinematic suppression, form-factor and reduced mass.

2.1.1 The effect of isospin violation

Given an element with atom number A , atomic number Z and the reduced mass of the element and DM particle $\mu_A = m_\chi m_A / (m_\chi + m_A)$. By assuming $m_p \approx m_n$, the usual DM-nucleus cross section is written as [6],

$$\sigma_{\chi A} = \frac{4\mu_A^2}{\pi} [Z f_p + (A - Z) f_n]^2 = A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A} \right)^2 \left[Z + (A - Z) \frac{f_n}{f_p} \right]^2 \sigma_{\chi p}. \quad (5)$$

where $\sigma_{\chi p}$ is the DM-proton scattering cross section. If the effective couplings of DM to protons, f_p , and neutrons, f_n , are not identical, the capture rate, Eq. (4), becomes

$$\Gamma_C^{\text{IV}} \propto \xi(\rho_0, \bar{v}, m_\chi) \left(\frac{\sigma_{\chi p}^{\text{IV}}}{\text{pb}} \right) \sum_{\mathcal{A}} F_{\mathcal{A}}^*(m_\chi) A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A} \right)^2 \left[Z + (A - Z) \frac{f_n}{f_p} \right]^2 \quad (6)$$

where $\xi(\rho_0, \bar{v}, m_\chi)$ is the first three terms in Eq. (4). The superscript IV stands for isospin violation. It is important to note that the $\sigma_{\chi p}^{\text{IV}}$ here is the DM-proton cross section derived from isospin violation condition and not identical to the $\sigma_{\chi p}$ in Eq. (4) in general.

2.1.2 Neutrino signal and atmospheric background event rates

The neutrino event rate in the detector from the Earth DM is given by

$$N_\nu = \int_{E_{\text{th}}}^{m_\chi} \frac{d\Phi_\nu}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega \quad (7)$$

where E_{th} is the detector threshold energy, $d\Phi_\nu/dE_\nu$ is the neutrino flux from DM annihilations, A_ν is the detector effective area [7, 8, 9], and Ω is the solid radian. The atmospheric background event rate has a similar expression,

$$N_{\text{atm}} = \int_{E_{\text{th}}}^{E_{\text{max}}} \frac{d\Phi_\nu^{\text{atm}}}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega. \quad (8)$$

We set $E_{\text{max}} = m_\chi$ in Eq. (8) to compare with the DM signal.

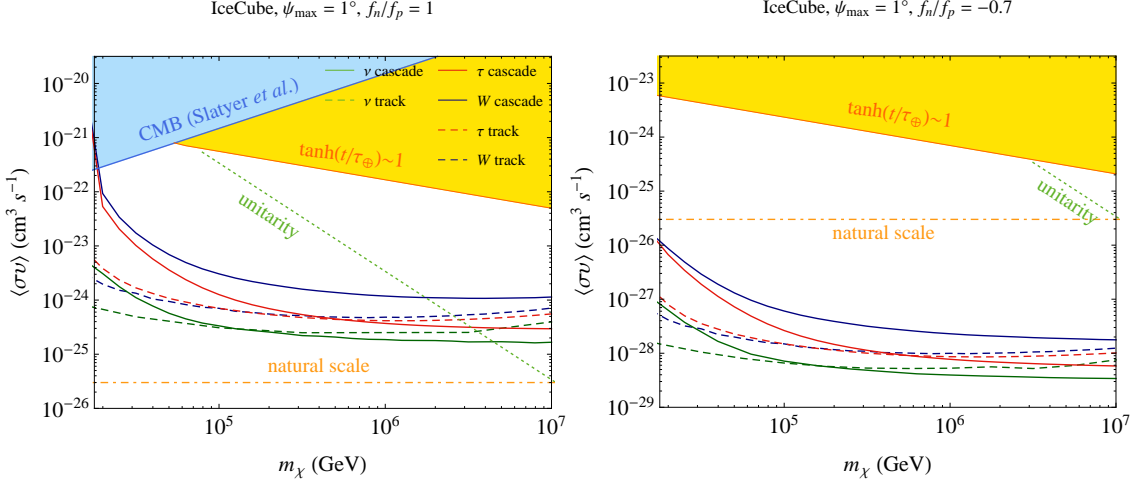


Figure 1: The IceCube 5-year sensitivity at 2σ to $\langle\sigma v\rangle$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with track and cascade events, respectively. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The yellow-shaded region is the parameter space for the equilibrium state and the blue-shade region is the constraint from CMB [11].

3 Results

We present the sensitivity as a 2σ detection significance in 5 years, calculated with the convention,

$$\frac{s}{\sqrt{s+b}} = 2.0 \quad (9)$$

where s is the DM signal, b the atmospheric background, and 2.0 referring to the 2σ detection significance. The atmospheric ν_τ flux is extremely small and can be ignored in our analysis. Thus we take ν_e and ν_μ as our major background sources. The detector threshold energy E_{th} in Eq. (7) and (8) is set to be 10^4 GeV in order to suppress the incoming background. In our analysis, we present two isospin scenarios for the constraints on $\langle\sigma v\rangle$ and $\sigma_{\chi p}$. One is $f_n/f_p = 1$, the isospin symmetry case, and the other is $f_n/f_p = -0.7$, the isospin violation one.

To constrain DM-annihilation cross section $\langle\sigma v\rangle$, we make use of the $\sigma_{\chi p}$ from the extrapolation of the LUX bound [10] to $m_\chi > 10$ TeV.

3.1 IceCube sensitivities

In Fig. 1 we present the IceCube sensitivities to $\langle\sigma v\rangle$ of $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels in the Earth core with both track and cascade events. In

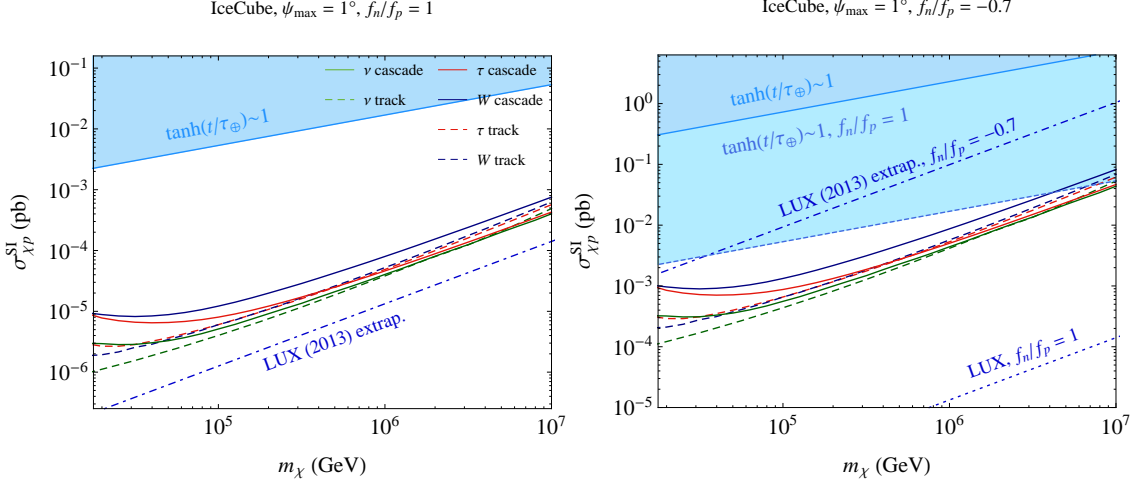


Figure 2: The IceCube 2σ sensitivities in 5 years to $\sigma_{\chi p}^{\text{SI}}$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with both track and cascade events. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The blue-shaded region is the parameter space for the equilibrium state and the light-blue-shaded region on the right panel refers to the equilibrium-state parameter space for the isospin symmetry case as a comparison. An extrapolation of current LUX limit has been shown on the figures.

$f_n/f_p = 1$, the IceCube sensitivities to track events from $\chi\chi \rightarrow \tau^+\tau^-$ and W^+W^- annihilation channels are comparable while one expects to obtain the most stringent constraint on the annihilation cross section by analyzing track and cascade events from $\chi\chi \rightarrow \nu\bar{\nu}$.

However, the isospin violation scenario, $f_n/f_p = -0.7$, will weaken the LUX bound by 4 orders of magnitude, i.e., the LUX upper bound on $\sigma_{\chi p}$ is raised by 4 orders of magnitude. With a 4-order larger $\sigma_{\chi p}$, the capture rate given by Eq. (6) is enhanced by 2 orders of magnitude since the suppression factor due to the isospin violation is around 10^{-2} for chemical elements in the Earth core. With the capture rate enhanced by 2 orders of magnitude, the IceCube sensitivities to $\langle\sigma v\rangle$ of various annihilation channels can be improved by about 4 orders of magnitude. Therefore, the sensitivities could reach below the natural scale $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}$.

Fig. 2 shows the IceCube sensitivities to spin-independent cross section $\sigma_{\chi p}^{\text{SI}}$ by analyzing track and cascade events from $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels in the Earth core. The threshold energy E_{th} is the same as before and we take $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}$ as our input. Precisely speaking, the sensitivity to $\chi\chi \rightarrow \nu\bar{\nu}$ channel is the highest. However, the sensitivities to different channels can be taken as comparable since the differences between them are not significant.

When isospin is a good symmetry, the IceCube sensitivities are no better than

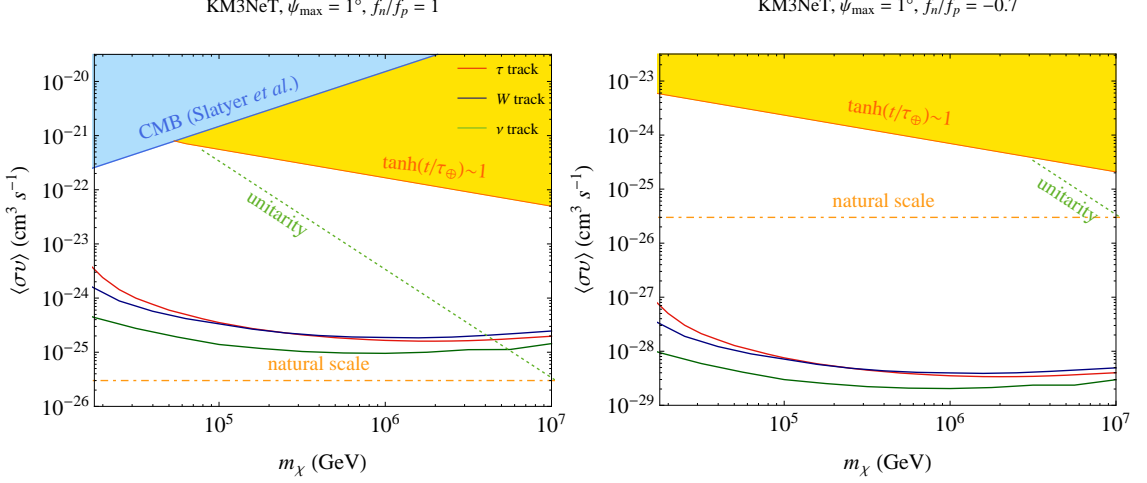


Figure 3: The KM3NeT 2σ sensitivities in 5 years to $\langle\sigma v\rangle$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with track events only. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The yellow-shaded region is the parameter space for the equilibrium state and the blue-shaded region is the constraint from CMB [11].

constraints from the LUX extrapolation. However, with $f_n/f_p = -0.7$, the capture rate in Eq. (6) is reduced to 1% of the isospin symmetric value. Therefore one requires 100 times larger $\sigma_{\chi p}^{\text{SI}}$ to reach the same detection significance. However, the ratio $f_n/f_p = -0.7$ makes a more dramatic impact to the DM direct search using xenon as the target. The DM scattering cross section with xenon is reduced by 4 orders of magnitude. Hence the indirect search by IceCube could provide better constraint on $\sigma_{\chi p}^{\text{SI}}$ than the direct search in such a case.

3.2 KM3NeT sensitivities

Besides IceCube, the neutrino telescope KM3NeT located in the northern-hemisphere shall also reach to a promising sensitivity in the near future. Therefore it is worthwhile to comment on the performance of KM3NeT. Since KM3NeT only publishes ν_μ charge-current effective area in the present stage, we shall only analyze track events.

The results are shown in Fig. 3 and 4 with parameters chosen to be the same as those for computing the IceCube sensitivities. The KM3NeT sensitivities are almost 1 order of magnitude better than the IceCube ones due to its ν_μ C.C. effective area is about one order of magnitude larger than IceCube's.

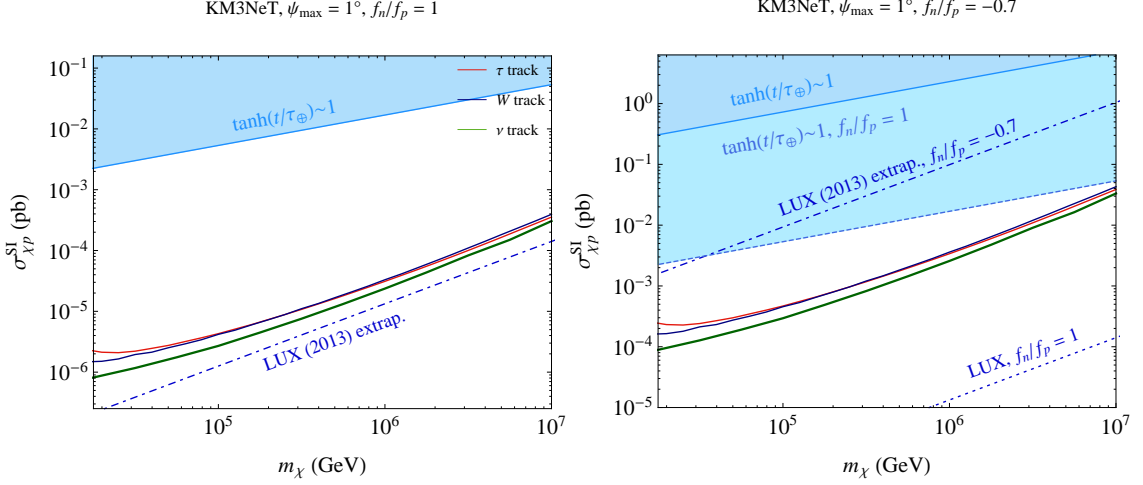


Figure 4: The KM3NeT 2σ sensitivities in 5 years to $\sigma_{\chi p}^{\text{SI}}$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels for track events only. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The blue-shaded region is the parameter space for the equilibrium state and the light-blue-shaded region on the right panel refers to the equilibrium-state parameter space in the isospin symmetry case.

4 Summary

In this work we have presented the IceCube and KM3NeT sensitivities to DM spin-independent cross section $\sigma_{\chi p}$ and annihilation cross section $\langle\sigma v\rangle$ by detecting DM induced signature from the Earth's core. The direct DM search only probes $\sigma_{\chi p}$ with the sensitivity dropping quickly with DM mass for $m_\chi > 10^4$ GeV. However, the indirect search using the large underground neutrino telescopes such IceCube or KM3NeT could probe $\sigma_{\chi p}$ in such a mass range. Besides, the indirect search can also probe $\langle\sigma v\rangle$.

We have also shown that, like the direct search, the indirect search is affected by the isospin violation. The implications of isospin violation to IceCube and KM3NeT observations have been presented in Sec. 3. Taking isospin violation effect into account, the sensitivities of the above neutrino telescopes to $\sigma_{\chi p}$ and $\langle\sigma v\rangle$ for different channels could be better than the direct search limit and the natural scale, respectively for a certain range of f_n/f_p .

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